Collectivity in intermediate-scale QGP and extended hydro. regime

Fluid  mesoscopy  parton gas

Hydro.  Extended Hydro. Regime

(characterized by $\eta, c_s^2, \ldots$)  (characterized by $\eta', \tau'_\pi, \ldots$)

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Weiyao Ke and YY, 2022.04XXXX
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QGP properties vs scale/gradient

- Unexplored regime: QGP at mesoscopic scale where typical gradient $k$ is too large for vHydro. and too short for pQCD.

- Exploring QGP mesoscopy:
  - Large angle scattering between jet and the medium.
  - Collectivity in small systems.

- This talk: medium response (how response changes with varying gradient).

e.g. Eramo, Rajagopal and YY, JHEP 19; Hulcher’s talk Tues. works by Kurkela, Mazeliauskas, Wiedemann, Bin Wu, ….
Medium response and excitations

- The (linear) response of a thermal system to an in-homogeneous disturbance is determined by excitations.

\[ O(t, \vec{k}) = A_H e^{-i\Omega_H(k)t} e^{-\Gamma_H(k)t} + \text{other excitations} \]

- In general, describing response is complicated as it involves various excitations.

- Simplification?
**Hydro. regime**

At small $k$, hydro. modes are gapped (smaller damping rate) from non-hydro excitations and hence dominate the response.

- Hydro. regime: $k < k_H$ where viscous hydro. works.

**What happens when $k > k_H$?**
The generality of extended hydro. regime (EHR)

Romatschke, EPJC 16'.

Amado-Hoyos-Landsteiner-Montero, JHEP 08

Extended hydro. regime (EHR):

- sound mode is gapped => “sound dominance”;
  See our upcoming paper for the discussion of shear channel.
- dispersion is different from vHydro.
- The presence of EHR seems generic; may be relevant for QGP.
The implication of EHR (if exists)

- The collectivity persists at intermediate gradient.
- Description of medium’s mesoscopy might be simplified.

NB: the notion of EHR bears a certain similarity to the far-from-equilibrium hydro. for expanding QGP. The main difference is that EHR describes perturbation around a bulk profile but not the bulk evolution itself.
Towards describing EHR

- Adding higher gradient terms (the radius of convergence; proliferation of inputs).

- An alternative: constructing a simple model with a few parameters such that
  - it reduces to hydro. in small k;
  - describes sound mode in (at least part of) EHR.

**MIS** (a simple yet non-trivial extension of Mueller-Israel-Stewart (MIS) eqns) serves the purpose.

*partly inspired by Hydro+, Stephanov-YY PRD 18’*
**MIS*: deforming MIS equation**

- Consider the decomposition: \( T^{\mu\nu} = T_{\text{ideal}}^{\mu\nu} + \pi^{\mu\nu} \)

- MIS Eqns

  \[
  D\pi^{\mu\nu} = -\frac{1}{\tau_\pi} \left( \pi^{\mu\nu} + \eta \partial^{<\mu} u^{\nu>} \right) - \ldots
  \]

  *shear strength*

- MIS* (for a conformal system):

  \[
  \pi^{\mu\nu} = -\eta' \partial^{<\mu} u^{\nu>} + \tilde{\pi}^{\mu\nu}
  \]

  \[
  D\tilde{\pi}^{\mu\nu} = -\frac{1}{\tau'_\pi} \left( \tilde{\pi}^{\mu\nu} + (\eta - \eta') \partial^{<\mu} u^{\nu>} \right) - \ldots
  \]

- MIS* parameters: \( \eta' \sim \) the effective viscosity in EHR and \( \tau'_\pi \) controls the boundary separating hydro. and EHR.

  \[
  \delta = \frac{\eta'}{\eta} \quad r = \frac{\tau'_\pi}{\tau_\pi}
  \]

  When \( \delta = 0 \),

  \( r = 0 \) (1st order hydro.);

  \( r = 1 \) (2nd order hydro).
**Flexibility/capability of MIS***

- Increasing $\delta = \eta' / \eta$ increases damping rate.
- Changing $r = \tau'_\pi / \tau_\pi$ varies boundary between hydro. and EHR.
- $(r, \delta)$ in combination controls sound propagation in EHR.
MIS* vs kinetic theory

\((\delta, r) = (0.25, 0.8)\)
\textbf{MIS* describes both kinetic and AdS/CFT theory in EHR}

RTA Kinetic: \((\delta, r) = (0.25, 0.8)\)  

AdS/CFT: \((\delta, r) = (0.25, 0.95)\)
Extended hydro. response for Bjorken expanding plasma

Motivation:

• complementing the study of a static medium;
• exploring the prospects of detecting EHR through jet-medium interaction.

Consider e.g. energy-energy response function.

\[ \delta \epsilon(\tau, x) = \int_{\tau_l}^{\tau} d\tau' \int_{x'}^x G_{ee}(\tau, \tau'; x - x') S_e(\tau', x') + \ldots \]

c.f. KOMPOST et al
RTA kinetic vs MIS*

\[ \bar{\tau} = \tau / \tau_R, \quad (\delta, r) = (0.15, 0.7) \]

Energy-energy response function. The disturbance is sourced at \( \tau_0 = \tau_R \) (equilibrated plasma).

- MIS* describes extended hydro. response.

\[ \Delta r = | \vec{x} - \vec{x}_0 | \]
\[ \Delta \tau = \tau - \tau_0 \]
MIS* describes energy-momentum response (5 different response funs) vs viscous hydro vs MIS

(δ, r) = (0.15, 0.7)
The success of MIS* confirms that in extended hydro. regime (EHR), the characterization of QGP mesoscopy can be simplified.

- Responses in different microscopic theory can be described by the same effective models such as MIS*.

- Properties are characterized by a few parameters.
We introduce extended hydro. regime (EHR) scenario for QGP-like system at intermediate scale and illustrate its generality.

- Collective excitations dominate even at intermediate gradient.
- The description at mesoscopic scale simplifies under EHR scenario.
- Observables: jet-medium interaction? small systems?
- Understanding the evolution of QCD at extreme density (HICs) may shed light on that at extreme virtuality (EICs).
Back-up
Shear channel

The domain of EHR is relatively narrow in shear channel for both kinetic theory/holography.